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| 13. ABSTRACT (maximum 200 words) During the course of this contract, we have developed several new olefin diphenyl-diacetylene and bistolane liquid crystals for laser communications. The olefin diphenyl-diacetylenes, synthesized by Mary Neubert's group of Kent State University, exhibit a much wider nematic range than the corresponding alkyl homologues. The high clearing point of the olefin compounds helps to increase the birefringence and figure-of-merit through higher order parameter. A sample eutectic mixture consisting of such olefin diphenyl-diacetylene compounds shows $\Delta n \sim 0.43$ at $\lambda = 1.06\mu m$. A major drawback of the diacetylene compounds is their inadequate UV stability. To overcome this, we have modified the molecular structures and developed some new bistolane liquid crystals. Owing to its long molecular conjugation, the melting point of bistolane exceeds 140°C. High melting point implies to poor solubility while forming eutectic mixtures. To lower melting point, methyl and ethyl substitutions in the middle phenyl ring have been found effective. Some ethyl-substituted bistolananes are liquid crystals at room temperature. However, the viscosity of the ethyl bistolanes is increased. The methyl substitution represents a compromise between melting temperature and viscosity. Prof. Hsu's group has helped us synthesize dozens of cyano and fluoro bistolanes. The Δn of the cyano bistolane was extrapolated to be 0.53 at $\lambda = 0.633\mu m$ and $T = 22^\circ C$. | | | |
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High Performance Liquid Crystals for Laser Communications

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Final Report

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High Performance Liquid Crystals for Laser Communications

1. Objectives:

The objective of this program is to develop high performance liquid crystal (LC) mixtures with ten times higher figure-of-merit than the benchmark commercial E7 mixture.

2. Status of Effort:

In collaboration with Professors Alex Seed and Mary Neubert of Kent State University and Prof. C. S. Hsu of National Chiao Tung University (Taiwan), we have developed some isothiocyanato naphthalene tolanes, olefin diphenyl-diacetylene and bistolane liquid crystals with birefringence greater than 0.5. The UV and thermal stability of these high birefringence liquid crystals is a concern. New molecular design strategies are developed.

3. Accomplishments

3.1 Motivation

High birefringence and low viscosity play crucial roles in enhancing the performance of liquid crystal based optical phased array, developed for laser beam steering. The shortcomings of these elongated molecules are high melting point, relatively high viscosity and poor UV stability. To take all these factors into consideration, optimal molecular structures remain to be discovered.

3.2 Optical Phased Array

The optical phased array (OPA) developed by Raytheon and AFRL, as shown in Fig.1, is a versatile device for laser beam steering and optical communications. The applied stepwise voltages create liquid crystal (LC) phase grating that deflects the incoming laser beam to a programmable angle with high precision. To steer a $\lambda=1.55\mu\text{m}$ laser beam, the required 2π phase change ($\delta=2\pi d\Delta n/\lambda$) leads to $d\Delta n \sim 1.6$; here d is the LC layer thickness. Although a thick LC layer would lead to a large phase shift, its response time is sluggish because the LC response time is proportional to d^2 . In order to achieve fast response time while keeping high manufacturing yield, the cell gap is normally kept at $d \sim 4\mu\text{m}$. Thus, LC mixtures with $\Delta n \geq 0.4$ and low viscosity, low optical loss, wide nematic range, and low operating voltage are desperately needed.

To compare the performance among various LC compounds, we have defined a figure-of-merit (FoM) as following:

$$FoM = K_{11}(\Delta n)^2 / \gamma_1 \quad (1)$$

In Eq.(1), K_{11} is the splay elastic constant and γ_1 is the rotational viscosity. Since K_{11} , Δn and γ_1 are all dependent on the temperature, FoM is sensitive to the operating temperature. In the low temperature regime, as the temperature is increased, the decreasing rate of γ_1/K_{11} is much faster than that of $(\Delta n)^2$ resulting in an enhanced FoM. As the temperature gets close to the clearing point (T_c) of the LC employed, the decreasing rate of γ_1/K_{11} gradually saturates while $(\Delta n)^2$ starts to decrease rapidly. As a result, FoM drops sharply as the temperature approaches T_c . Therefore, FoM has a maximum value at a temperature called optimal operating temperature (T_{op}). For a given LC mixture, T_{op} is about 20°C below T_c . Operating an OPA at a higher temperature would boost FoM, however, the long-term stability of the driving electronics and LC medium should be taken into consideration.

For laser beam steering application, our objective is to develop new liquid crystal mixtures exhibiting $FoM > 70 \text{ ms}/\mu\text{m}^2$ at $T < 70^\circ\text{C}$ while possessing good photo and thermal stability, low operating voltage and low absorption loss.

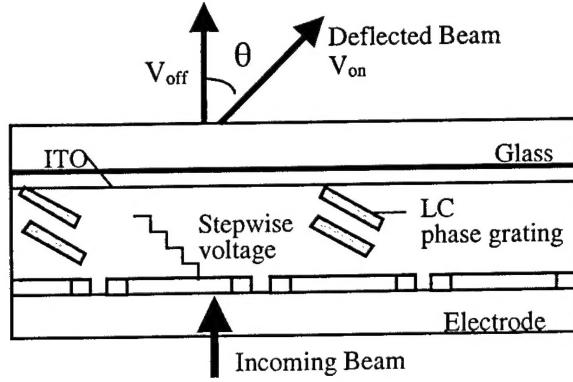


Fig.1 A sketch of a LC-based optical phased array. The applied stepwise voltage generates LC phase grating that deflects the incoming laser beam.

3.3 LC Birefringence

Based on the single band model, the LC birefringence is expressed as:

$$\Delta n = G \frac{\lambda^2 \lambda^{*2}}{\lambda^2 - \lambda^{*2}} \quad (2)$$

In Eq.(1), $G \sim NZS(f_{\parallel} - f_{\perp})$, where N is the molecular packing density, Z is the number of participating electrons, S is the order parameter that governs the temperature effect, $(f_{\parallel} - f_{\perp})$ is the differential oscillator strength, and λ^* is the mean resonance wavelength.

From Eq.(2), the LC birefringence is mainly determined by the molecular conjugation length, differential oscillator strength (i.e., molecular shape and size), and temperature. When the temperature is far below the clearing point, the order parameter can be approximated by:

$$S = (1 - T/T_c)^\beta \quad (3)$$

For many LC compounds studied, $\beta \sim 0.25$ is nearly a constant and is insensitive to materials.

Based on Eqs. (2) and (3), an effective way for increasing Δn is to search for short chain and linearly conjugated molecules. Such linear LC compounds tend to exhibit high Δn , relatively low viscosity and high clearing point. A major drawback of the highly conjugated compounds is high melting point. A well known example is 5CT (cyanoterphenyl); its nematic range is from 131°C to 240°C. Therefore, in order to lower the melting point to -40°C for storage purpose, eutectic mixtures consisting of more than 10 components are rather common.

Another serious concern for high birefringence LCs is their photo and thermal stability. To prevent LC material from interacting with moistures, a LC cell is hermetically sealed. An incoherent UV light is used to cure the glue lines before injecting LC mixture and then plug the hole after vacuum filling the LC device. Thus, the LC material has to withstand at least 30 seconds of intense UV exposure ($I \sim 100 \text{ mw/cm}^2$) without degradation. Moreover, the LC device is expected to operate at elevated temperatures in order to obtain high speed. Excellent thermal stability is another important criterion.

In the visible spectral region, Δn decreases as the wavelength increases. For an OPA operating at $\lambda = 1.55 \mu\text{m}$, the condition $\lambda \gg \lambda^*$ holds and Eq.(2) is reduced to $G\lambda^{*2}$, which is insensitive to the wavelength. That means, the LC birefringence in the near IR region is basically a constant, mainly governed by G and λ^* . For a LC with $\lambda^* = 250 \text{ nm}$,

its Δn at $\lambda=1.55\mu\text{m}$ is about 23% lower than that at $\lambda=550\text{nm}$. Therefore, in order to obtain $\Delta n=0.4$ at $\lambda=1.55\mu\text{m}$, the compounds should possess $\Delta n\sim 0.5$ at $\lambda=550\text{nm}$.

3.4 LC Compounds with $0.4 < \Delta n < 0.5$

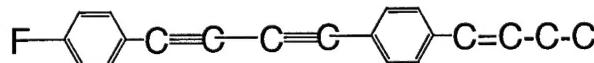
In this category, diphenyl-diacetylenes and tolanes are chosen as examples. Diphenyl-diacetylenes exhibit many nice physical properties, however, their photo and thermal stability is inadequate. On the other hand, tolanes have better stability except their molecular conjugation is not long enough. An electron acceptor polar group, e.g., CN or NCS needs to be attached for enhancing birefringence.

A. Diphenyl-diacetylenes (PTTP)

The asymmetric diphenyl-diacetylenic liquid crystals (abbreviated as PTTP; P=phenyl ring, T= carbon-carbon triple bond), as shown below, exhibit a high Δn , low viscosity and wide nematic range.



Both alkyl, alkenyl, and fluoro PTTP homologues have been synthesized. Replacing the alkyl side chain by an alkenyl (as shown below) dramatically enhances the clearing point and widens the nematic range:



For example, alkyl PTTP-4F has quite narrow nematic range (from 85.4 to 87.7°C). By replacing the alkyl side chain with an alkenyl, the nematic range of PTTP-4d1,F is extended from 89.1 to 163.1°C. High clearing point also plays an important role in improving birefringence due to higher order parameter. Mixtures consisting of these olefin PTTP homologues exhibit $\Delta n\sim 0.43$ at $\lambda=633\text{nm}$ and $T=20^\circ\text{C}$.

Three mixtures (designated as A, B and C) consisting of different PTTP components were formulated and their FoM evaluated at elevated temperatures. Results are compared to a commercial mixture E7 as shown in Fig.2. Mixture A is a eutectic mixture consisting of PTTP-24, -36, -4F and -6F. Its clearing point is 90°C and maximum FoM reaches $20\mu\text{m}^2/\text{s}$ at $T=65^\circ\text{C}$. Mixture B is a binary olefin PTTP mixture consisting of 47% PTTP-4d1,F and 53% PTTP-5d1,F. Its clearing point is as high as 163°C and FoM reaches $80\mu\text{m}^2/\text{s}$ at $T\sim 80^\circ\text{C}$. Unfortunately, mixture B's melting point is too high (78°C) for practical applications. To lower the melting point, we added some non-polar alkenyl PTTP homologues (PTTP-2,4d1, -2,5d2 and -3,6d1) to form mixture C. The nematic range of mixture C is from 6 to 156°C. Its FoM reaches $40\mu\text{m}^2/\text{s}$ at $T\sim 80^\circ\text{C}$.

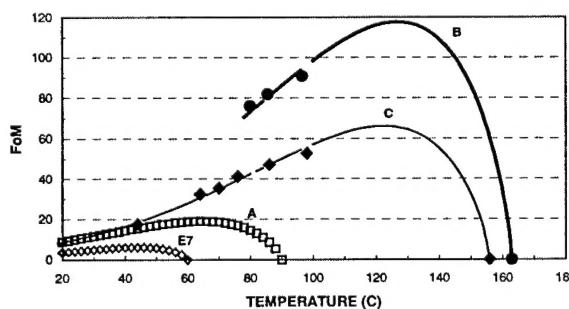
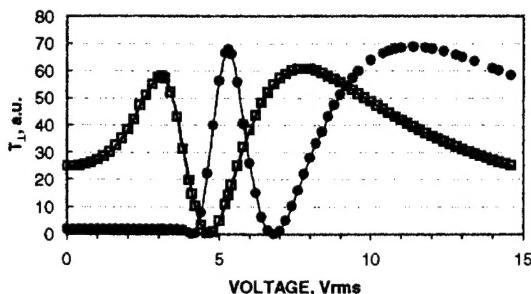


Fig.2 The temperature-dependent FoM (in unit of $\mu\text{m}^2/\text{s}$) of E7, mixtures A, B and C. $\lambda=633\text{nm}$.

Inadequate photo and thermal stability is a major concern for the PTTP compounds. Figure 3 shows the measured voltage-dependent transmittance of a homogeneous cell before and after UV exposure. The LC used is PTTP-24/36 binary mixture (50% PTTP-24 and 50% PTTP-36). The UV light intensity was measured to be $I=50\text{mw}/\text{cm}^2$ and central wavelength at $\lambda\sim 365\text{nm}$. Dots represent experimental results at $t=0$ and squares are exposed with UV light for 65 seconds.

length at $\lambda \sim 365\text{nm}$. Dots represent experimental results at $t=0$ and squares are exposed with UV light is.



3 The voltage-dependent transmittance of a homogeneous LC cell before (dots) and after (squares) UV exposure. UV intensity $I=50\text{mw/cm}^2$. Cell gap $d=3.74\mu\text{m}$, probing laser $\lambda=633\text{nm}$ $T=22^\circ\text{C}$. Alignment layer is buffed polyimide film. Crossed polarizers. Exposure time=65 seconds.

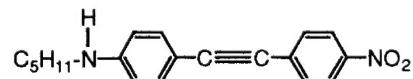
three general phenomena are observed when degradation occurs: 1. The effective Δn is decreased, 2. threshold voltage is smeared and decreased, and 3. The light scattering intensity is increased. The degradation is believed to originate from the UV-induced free radicals of the diacetylene group. These free radicals migrates to the neighboring PTTP molecules, converting triple bond into double bond and initiating the cross-linking process from front surface layers and gradually migrating into bulk as UV dosage increases. Once these layers are cross-linked, the surface alignment is disturbed resulting in a reduced Δn , increased viscosity, threshold voltage, and increased light scattering.

(a) and (b) show the photos of a $6-\mu\text{m}$ homogeneous-aligned LC cell taken under a polarizing optical microscope before and after UV exposure, respectively. Before UV exposure, the cell shows uniform green color under crossed-polarizers. After 85 seconds of exposure at $I \sim 50\text{mw/cm}^2$, the cell turned to different color and polymerized textures appeared. These polymerized clusters scatter light, disturb LC alignment and increase light scattering. As a result, the observed birefringence is decreased, and threshold voltage is smeared and reduced.



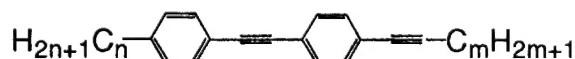
4 Microscope photos of a $6-\mu\text{m}$ homogeneous LC cell before (a) and after (b) UV exposure for 85 seconds. Note the color change and polymerized textures in (b).

In the polymerization process, an UV scavenger as shown below has been discovered. Adding 10% of nitrobenzylamine to PTTP-24/36, the mixture's UV stability is significantly improved.



Compounds

Acetylene causes material instability, these two acetylene groups should be separated. One possibility is to have one acetylene group outside the phenyl rings, as shown below:



From Table I, these PTPT compounds exhibit either monotropic phase or no LC phase at all. The monotropic phase is undesirable for mixture applications owing to its high melting temperature. For a normal LC, we prefer low melting and high clearing points.

Table I Phase transition temperatures of some Chisso and Merck PTPT-nm compounds.

| n | m | Phase Transition (°C) |
|---|---|-----------------------|
| 2 | 2 | K 83.1 I |
| 2 | 3 | K 89.8 I |
| 3 | 1 | K 87.7 N (85.1) I |
| 3 | 2 | K 100.1 N (48.7) I |
| 3 | 3 | K 78.0 N (54.0) I |
| 3 | 5 | K 72.0 N (40.4) I |
| 4 | 1 | K 81.0 N (56.9) I |
| 4 | 2 | K 87.6 N (76.8) I |
| 4 | 3 | K 100.9 N (65.0) I |
| 4 | 4 | K 84.3 I |
| 5 | 2 | K 80.8 N (46.1) I |
| 5 | 3 | K 76.2 N (50.3) I |

The UV absorption spectrum of PTPT-35 (circles) was measured and results are compared with PTTP-24 (squares) as shown in Fig.5. Although these two LCs consist of similar core structure, PTTP has a slightly longer conjugation than the alternating PTPT.

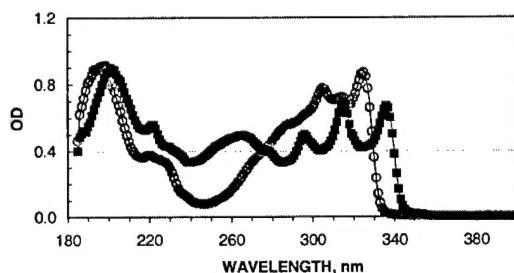


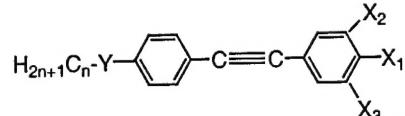
Fig.5. Measured optical density of PTPT-35 (gray) and PTTP-24 (black). Concentration=1%, d=6μm, and host ZLI-2359.

C. Tolanes (PTP)

Many tolanes derivatives, as shown in Table II, have been studied. Some cyano (CN) and isothiocyanato (NCS) tolanes exhibit either monotropic or smectic phase so that they are unfavorable for forming nematic mixtures. Replacing the alkyl side chain with an alkenyl group the monotropic phase is converted to enantiotropic nematic phase. Such compounds possess a wide nematic range, lower melting point, and higher Δn as compared to their parent compound. The extrapolated Δn of these tolanes exceeds 0.4.

Both CN and NCS polar groups are effective electron acceptors. They effectively extend the electron conjugation so that the LC birefringence is significantly enhanced. They also possess a large dipole moment (4 Debye for CN and ~3.6 Debye for NCS). However, the cyano compounds tend to form dimers so that their viscosity is high. Thus, NCS is more favorable than CN for achieving high birefringence, low viscosity, and large dielectric anisotropy. The major challenges of the NCS compounds are in two aspects: 1. Their synthesis procedures are more complicated, and 2. The NCS compounds usually favor smectic phase.

Table II Physical properties of some tolane derivatives. Here, K, N, and I represent crystalline, nematic and isotropic phase, respectively, () stands for monotropic phase transition, Ph in column Y stands for a phenyl ring.



| X ₁ | X ₂ | X ₃ | n | Y | Phase Transitions | Δn |
|----------------|----------------|----------------|---|----|-----------------------------|------|
| CN | H | H | 3 | - | K 87 N (78) I | |
| CN | H | H | 3 | O | K 98 N 103 I | |
| CN | H | H | 3 | ≡ | K 119 N (87) I | 0.46 |
| CN | H | H | 3 | = | K 100 N 150 I | 0.47 |
| CN | F | H | 3 | ≡ | K 109 I | 0.41 |
| CN | F | H | 3 | = | K 74 N 102 I | 0.43 |
| CN | H | H | 4 | S | K 80 N (53) I | 0.34 |
| NCS | H | H | 4 | S | K 84.8 SmB 85.4 N (65) I | 0.49 |
| NCS | H | H | 5 | - | K 92 SmA (82) I | |
| NCS | F | F | 4 | O | K 71 N (62) I | 0.41 |
| NCS | F | F | 4 | Ph | K 63 SmA 100 N 209 I | 0.46 |

It should be mentioned that the LC compounds containing CN or NCS group usually exhibit a low resistivity. However, recent studies show that if at least X₂ or X₃ is a fluoro group, the voltage holding ratio is boosted to 98%. Such fluoro group also contributes to enhance the dielectric anisotropy. The tradeoff is in the increased viscosity.

Figure 3 shows the UV stability of the pentyl-isothiocyanato-tolane (PTP-5NCS). Since PTP-5NCS is smectic, we mixed 20% in an UV transparent nematic mixture ZLI-2359. A 6-μm homogeneous cell was prepared for UV tests. A HeNe laser was used to probe the electro-optic properties of the LC cell. From Fig.3, the extrapolated UV stability of PTP-5NCS is about 40 minutes at I~50mw/cm² exposure intensity, which is much better than that of the PTTP-nm compounds (~20 seconds). The absorption wavelengths of PTTP and PTP-5NCS are similar. Therefore, electronic transition wavelength is not the sole factor affecting the stability of the LC material. Molecular structure also plays an important role.

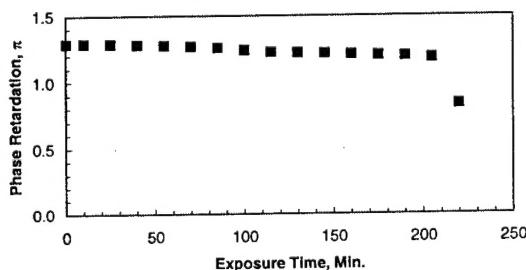


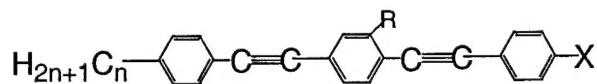
Fig.3 The measured phase retardation of a d~6-μm homogeneous cell containing 20% PTP-5NCS in ZLI-2359. UV intensity I~50mw/cm². λ=633nm.

3.5 LCs with Δn >0.5

Two series of LC compounds with Δn>0.5 at λ=589nm have been reported. They are bistolanes and isothiocyanato naphthalene tolanes.

A. Bistolanes

Bistolanes exhibit high Δn due to their long molecular conjugation. However, as the conjugation length increases, their melting point also increases. Based on the Schröder-van Laar equation, high melting point leads to a poor solubility for forming eutectic mixtures. An effective way to lower melting point is to substitute a lateral alkyl group in the middle phenyl ring, as shown below, to widen the molecular separation:



Here, X can be an F, CN or NCS group, and R can be a hydrogen, methyl, ethyl or fluoro group.

Table III lists the phase transition temperatures of some fluoro and cyano bistolanes. The compound with R=H has melting point as high as 173°C. Thus, its solubility is less than 5%. With a fluoro substitution, the melting point is decreased to 146°C. In the case that R=CH₃, the melting point is reduced to 69°C. Continuing to increase the lateral side chain length, such as C₂H₅, will lower the melting point further, however, its viscosity increases substantially. The extrapolated Δn of a cyano bistolane (with R=CH₃) is 0.53.

As the molecular conjugation length increases, the LC becomes bulkier so that its viscosity also increases. To reduce viscosity, elevated temperature (40-50°C) operation has been commonly considered. Roughly speaking, the viscoelastic coefficient (γ_1/K) declines two times as the operating temperature increases by every 15°C.

Table III Phase transitions (in °C) and heat fusion enthalpy (kcal/mol) of some bistolanes.

| n | R | X | T _{mp} | T _c | Δn |
|---|----|----|-----------------|----------------|------------|
| 4 | H | F | 173 | 207 | 7.6 |
| 4 | F | F | 146 | 170 | 6.5 |
| 5 | Me | F | 69 | 163 | 5.0 |
| 5 | Et | F | 61 | 103 | 5.2 |
| 5 | Me | CN | 114 | 203 | 5.5 |
| 5 | Et | CN | 85 | 159 | 3.5 |

The UV stability of a dialkyl bistolane PTP(3-Et)TP-53 was studied. At I=50mw/cm² intensity, PTP(3-Et)TP-53 can only withstand about 2 minutes of UV exposure. The photo stability of a LC is determined by its absorption wavelength and chemical structure. Fig.6 shows the absorption wavelength of three compounds studied: PTTP-4F, PTP-5NCS and PTPTP-52. During experiment, 1% of the guest compound was dissolved in an UV transparent LC mixture, ZLI-2359. A d~6μm homogeneous cell was used for the absorption measurements. From Fig.6, the absorption tail of PTPTP-52 is on the edge of the central UV light. Thus, its UV stability is much worse than that of PTP-5NCS.

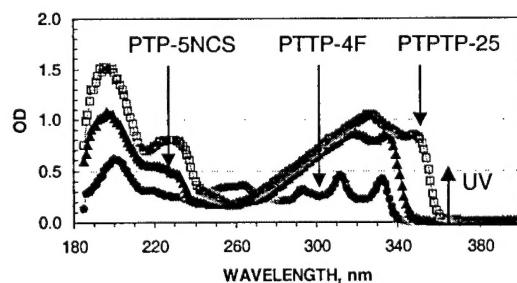


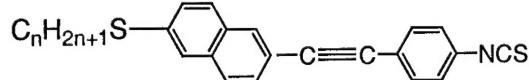
Fig.6 UV absorption spectra of PTTP-4F, PTP-5NCS and PTPTP-52. Concentration=1%, cell gap d=6μm and host LC is ZLI-2359.

Also observed from Fig.6, the absorption tail of PTTP-4F and PTP-5NCS extends to 340nm and 350nm, respectively. Although PTP-5NCS has a slightly longer absorption, it can still withstand ~40 minutes of UV

irradiation as compared to 30 seconds for PTTP-4F. Thus, chemical structure also plays an important role in determining the UV and thermal stability.

B. Isothiocyanato Naphthalene Tolanes

Another series of nematic LC with $\Delta n > 0.5$ is the isothiocyanato naphthalene tolane (with structure shown below reported by the Hull University).



Prof. Alex Seed of Kent State University has synthesized the $n=3-5$ homologues for our evaluation. The $n=4$ homologue shows $\Delta n \sim 0.54$ and nematic range from 91.5 to 136.7°C. The naphthalene group not only lengthens the molecular conjugation, but also suppresses the smectic phase. Owing to its elongated structure, its photo and thermal stability cannot match with that of the simple NCS tolanes. However, the naphthalene NCS tolane exhibits an enantiotropic nematic phase. It is more favorable for forming eutectic mixtures.

3.6 LC Absorption

A. Visible to Near IR

For high power laser beam steering in the near IR region, the LC absorption is a critical issue because some overtone molecular vibration bands exist. Two factors contribute to the optical loss: light scattering and absorption. To suppress light scattering, the LC mixture under study was heated to an isotropic state. In addition, in order to take surface reflections into consideration, a 1-mm gap quartz cell was used in the reference channel and a 2-cm cell used as sample. Therefore, the measured optical loss is equivalent to a 1.9-cm LC layer. For such absorption measurements, ~1g of sample is required. Thus, we chose Merck E7 mixture ($T_c = 60^\circ\text{C}$) for such studies. Both sample and reference cells were controlled at $T \sim 70^\circ\text{C}$. Results are depicted in Fig.7.

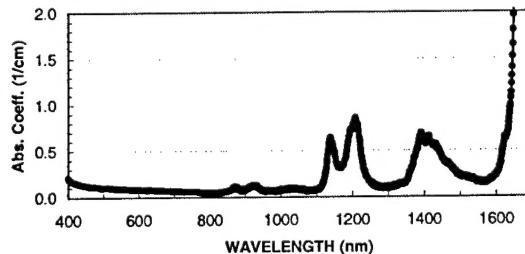


Fig.7 Measured absorption coefficient of an E7 LC cell in the visible and near IR regimes. $T \sim 70^\circ\text{C}$. $d = 1.9\text{cm}$.

From Fig.7, E7 has relatively small absorption in the visible region. This is because the $\pi \rightarrow \pi^*$ electronic transitions of E7 are located in the UV region. As the wavelength gets further apart from resonance, absorption decreases. The absorption minimum occurs at near IR ($\lambda \sim 850\text{nm}$) region. At $\lambda = 1.06\mu\text{m}$, $\alpha \sim 0.08 \text{ cm}^{-1}$. Thus, the LC-based OPA should be able to steer high power YAG laser beams. Usually, in a LC panel, the conductive and transparent ITO layer has the lowest damage threshold ($\sim 200\text{MW/cm}^2$). To avoid laser-induced phase transition to occur, a high T_c LC mixture is preferred.

Beyond $\lambda = 1.1 \mu\text{m}$, the overtone vibration bands appear. At $\lambda = 1.3$ and $1.55\mu\text{m}$ (two laser wavelengths commonly used for fiber-optic communications), the LCs we studied all exhibit absorption valleys. At these two wavelengths, the absorption coefficients of E7 are 0.1 and $0.15/\text{cm}$, respectively. Suppose a $5\text{-}\mu\text{m}$ cell gap is used for the $\lambda = 1.55\mu\text{m}$ optical switch, the absorption loss is quite negligible.

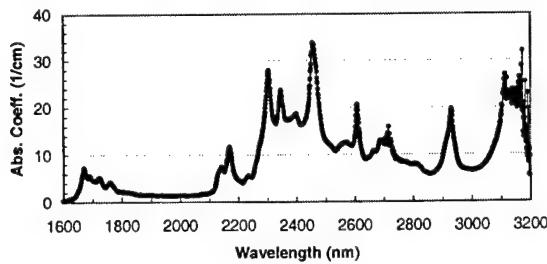


Fig.8 Measured IR absorption coefficient of an E7 LC cell at T~70°C. d=1.9cm.

B. Mid IR

In the longer IR region ($\lambda > 2.1\mu\text{m}$), several overtone molecular vibration bands exist and overlap closely. As a result, the background absorption coefficient reaches $\alpha \sim 10\text{cm}^{-1}$, as shown in Fig.8. For a 5- μm cell, the absorption loss accounts for 0.5%. The absorbed laser light will be converted to heat and warm up the LC medium.

4. Personnel Supported

Myself and a part-time technician.

5. Publications: (1998-2001)

1. S. T. Wu and C. S. Wu
“A biaxial film-compensated thin homogeneous cells for reflective liquid crystal displays”
J. Appl. Phys. 83, 4096-4100 (1998)
2. S. T. Wu and C. S. Wu
“Optimization of film-compensated homogeneous cells for liquid crystal displays”
Liq. Cryst. 24, 811-818 (1998)
3. S. T. Wu, “A chiral-homeotropic cell with 2.5V operation voltage”
SID Tech. Digest 29, 754-7 (1998)
4. S. T. Wu and C. S. Wu
“Biaxial film-compensated thin homogeneous cells for reflective display”
SID Tech. Digest 29, 770-3 (1998)
5. S. T. Wu, “Overview on reflective liquid crystal displays”
(Invited) *Proc. SPIE* 3421, 84-97 (1998)
6. Dai-Liang Ting, Chieh-Li Chen, Chen-Lung Kuo, Yong-Hong Lu, Chung-Kuang Wei, Hsueh-Feng Shih, Chia-Wei Hao, and S. T. Wu
“Full Color Reflective type TFT-LCD” *Proc. SPIE* 3421, 106-112 (1998)
7. Kuen-Torng Tsay, Chain-Shu Hsu, and S. T. Wu
“Synthesis of asymmetric tolane liquid crystals for display application”
Proc. SPIE 3421, 142-150 (1998)
8. S. T. Wu
“Absorption measurements of liquid crystals in the UV, visible and infrared”
J. Appl. Phys. 84, 4462-5 (1998)
9. S. T. Wu, Q. T. Zhang, S. Marder
“High dielectric dopants for low voltage liquid crystal operation”
Jpn. J. Appl. Phys., 37, L1254-6 (1998)

10. S. T. Wu, "Low operation voltage liquid crystal devices"
(Invited paper) 5th International Display Workshops Proceedings (1998), pp. 69-72.
11. S. T. Wu and C. S. Wu
"Bisection effect on the twisted-nematic cells"
Jpn. J. Appl. Phys. 37, L1497-1500 (1998)
12. S. T. Wu, C. S. Hsu, K. F. Shyu
"High birefringence and wide nematic range double tolane liquid crystals"
Appl. Phys. Lett. 74, 344 (1999)
13. S. T. Wu, C. S. Hsu and Y. Y. Chuang
"Room temperature bis-tolane liquid crystals"
Jpn. J. Appl. Phys. 38, L286-8 (1999)
14. S. T. Wu
"Molecular designs of liquid crystals"
Electronics and Materials, 1, 100-104 (1999)
15. S. T. Wu, C. S. Hsu, K. F. Shyu, Y. Y. Chuang, H. B. Cheng, Z. Chai, G. Day, L. Guo and L. R. Dalton
"High birefringence bis-tolane liquid crystals for display applications"
SID Tech. Digest, 30, 706-9 (1999)
16. C. L. Kuo, C. L. Chen, D. L. Ting, C. K. Wei, B. D. Liu, C. W. Hao, and S. T. Wu
"Full color reflective-type TFT-LCD"
Journal of SID 7, 109-114 (1999)
17. S. T. Wu, C. S. Wu and C. L. Kuo
"Comparative studies of single-polarizer reflective liquid crystal displays"
Journal of SID 7, 119-126 (1999)
18. S. T. Wu and C. S. Wu
"Mixed-mode twisted nematic cell for transmissive liquid crystal display"
(Invited paper) J. Displays 20, 231-236 (1999).
19. S. T. Wu, R. N. Schwarz, Q. T. Zhang, S. Marder and C. S. Hsu
"Colorless high dielectric compounds for low voltage liquid crystal application"
(Invited paper) MRS Symposium Proceedings "Liquid crystal materials and devices" 559, 235-242 (1999).
20. K. J. Chen, S. T. Hong, W. C. Hu, J. L. Lin and S. T. Wu
"Negative dielectric anisotropy liquid crystal mixtures for TFT-LCD applications"
Proc. of the 6th International Display Workshops (Sendai, Japan, Dec. 1-3, 1999), pp. 73-76
21. K. J. Chen, D. C. Chen, S. T. Hong, W. C. Hu, J. L. Lin and S. T. Wu
"Liquid crystal mixtures for vertical-aligned TFT-LCDs" (In Chinese)
Proc. 1999 CICHE Annual Meeting (Hsinchu, Taiwan), Specialty Chemicals Technology and Applications, pp. 95-98
22. J. Colegrove, H. Yuan, S. T. Wu, J. R. Kelly, C. Bowley, G. P. Crawford
"Drive-Voltage Reduction for HPDLC Displays"
Proc. of the 6th International Display Workshops (Sendai, Japan, Dec. 1-3, 1999), pp. 105-108
23. S. T. Wu, C. S. Hsu, Y. Y. Chuang and H. B. Cheng
"Physical properties of polar bis-tolane liquid crystals"
Japanese J. Appl. Phys. Part II, 39, L38-41 (2000)

24. Y. J. Liao, C. S. Hsu and S. T. Wu
“Dipping and photo-induced liquid crystal alignments using silane surfactants”
Japanese J. Appl. Phys. Part II, 39, L90-93 (2000)
25. C. S. Hsu, K. F. Shyu, Y. Y. Chuang and S. T. Wu
“Synthesis of laterally substituted bistolane liquid crystals”
Liq. Cryst. 27, 283-7 (2000)
26. W. C. Lee, C. S. Hsu and S. T. Wu
“Liquid crystal alignment with a cross-linkable and solvent-soluble polyimide film”
Jpn. J. Appl. Phys. 39, L471-473 (2000)
27. L. H. Wu, W. C. Lee, C. S. Hsu and S. T. Wu
“Photo-induced liquid crystal alignment with discotic films”
Jpn. J. Appl. Phys. 39, 5899-5903 (2000)
28. S. T. Wu, M. Neubert, S. S. Keast, D. G. Abdallah, S. N. Lee, M. E. Walsh, T. A. Dorschner,
“Wide nematic range alkenyl diphenyl-diacetylene liquid crystals”
Appl. Phys. Lett. 77, 957-9 (2000)
29. L. H. Wu, shr-jie luo, C. S. Hsu and S. T. Wu
“Obliquely tilted discotic phase compensation films”
Jpn. J. Appl. Phys. 39, 1869-871 (2000)
30. S. T. Wu and G. Xu
“Cell gap and twist angle determinations of a reflective liquid crystal display”
IEEE Trans. Electron Devices ED-47, 2290 (2000)
31. L. H. Wu, W. C. Lee, C. S. Hsu and S. T. Wu
“Photo-alignment of liquid crystals using a cross-linked discotic film”
Liq. Cryst. 28, 317 (2001)
32. S. T. Wu
“High birefringence liquid crystals for displays and optical communications”
(Invited paper) SID Tech. Digest 32, 954-7 (2001)
33. S. T. Wu and D. K. Yang, “Reflective Liquid Crystal Displays” (335 pages, Wiley-SID, 2001).

6. Interactions or Transitions:

A. Presentations

1. J. A. Kornfield, M. D. Kempe, S. T. Wu and C. K. Ober
“Polymer solutions and gels in nematic solvents”
The Society of Rheology: 71st Annual Meeting, paper SG7, Madison, Wisconsin (Oct. 18, 1999)
2. S. T. Wu, C. S. Hsu, K. F. Shyu, Y. Y. Chuang and H. B. Cheng
“Polar bistolane liquid crystals”
(Invited Talk) 1999 International Chinese Liquid Crystal Conference, National Chiao Tung University, Hsinchu, Taiwan (Dec. 28-29, 1999)
3. S. T. Wu
“Low voltage liquid crystal displays”
(Invited Talk) Unipac Opto-Electronics, Hsinchu, Taiwan (Dec. 30, 1999)
4. S. T. Wu
“Reflective liquid crystal displays”
(Invited Talk) Wintek Inc., Tai-Chung, Taiwan (Dec. 31, 1999)

5. S. T. Wu
“High birefringence and low voltage liquid crystals”
(Invited Talk) DigiLens, Inc. Sunnyvale, California (Feb.25, 2000).
6. S. T. Wu
“Fast response liquid crystals”
(Invited Talk) Taipei SID Annual Meeting (March 10, 2000).
7. S. T. Wu
“Liquid crystals for mobile and laser communications”
(Invited Talk) Department Seminar, UCLA Materials Science & Eng. (April 14, 2000)
8. S. T. Wu
“Reflective liquid crystal displays for wireless communications”
(Invited Talk) Department Seminar, School of Optics, University of Central Florida (May 26, 2000)
9. S. T. Wu
“High birefringence liquid crystals”
AFOSR LC MURI, California Institute of Technology, Pasadena (June 22-23, 2000)
10. S. T. Wu
“High performance liquid crystals for laser beam steering”
(Invited Talk) ALCOM Optical Beam Steering Symposium, Liquid Crystal Institute, Kent State University (June 29-30, 2000)
11. S. T. Wu
“Liquid crystal materials for display applications”
(Invited Lecture) 6th Asia SID Workshop (Xi-An, China; October 18, 2000) (~100 attendees)
12. S. T. Wu, J. A. Ho, and B. G. Wu
“High brightness and low voltage cholesteric displays”
(Invited Talk) 6th Asia SID Conference (Xi-An, China; October 19, 2000)
13. S. T. Wu
“Reflective liquid crystal displays for mobile communications”
(Invited Talk) Acer Display Technology, Inc., (Hsinchu, Taiwan; October 23, 2000) (~150 attendees)
14. S. T. Wu
“Will reflective liquid crystal displays overtake transmissive ones?”
(Invited Talk) ITRI Inter-Laboratory seminar, (Hsinchu, Taiwan; December 15, 2000) (~100 attendees)
15. S. T. Wu
“High birefringence liquid crystals for telecom and microdisplay applications”
(Invited Talk) Third Overseas Chinese LC Conference, (National Cheng-Kung University, Taiwan; December 18-19, 2000) (~150 attendees)
16. S. T. Wu
“Advances on reflective liquid crystal displays”
(Invited Talk) SID Taipei Chapter (Hsinchu, Taiwan; December 21, 2000) (~200 attendees)
17. S. T. Wu
“Molecular engineering of liquid crystals for display applications”
(Invited Talk) Hong Kong University of Science and Technology (Feb. 26, 2001)
18. S. T. Wu
“New trends in liquid crystal displays”

(Invited Talk) ERSO/ITRI TAC Meeting (Hsinchu, Taiwan; March 2, 2001) (~100 attendees)

19. S. T. Wu
"Highlights on liquid crystals"
(Invited Lecture) UCLA Material Science & Engineering (April 24, 2001)
20. S. T. Wu
"High birefringence liquid crystals for displays and optical communications"
(Invited Talk) SID Annual Symposium (June 5-7, 2001 at San Jose, CA)

B. Transitions

1. We shipped a high dielectric compound to dpiX Corp. for testing. The dpiX team achieved a 2X reduction in the operating voltage of a holographic polymer-dispersed liquid crystal device. Contact person: Dr. Haiji Yuan (He left dpiX in 1999).
2. We shipped two high birefringence liquid crystal sample mixtures to Advanced Display Systems, Texas, and achieved a 2X improvement in cholesteric display brightness. Contact person: Dr. Bao-Gang Wu. His telephone number is (806) 335-2255 x201.
3. We helped Dr. Terry Dorschner of Raytheon Lexington Lab to improve the response time and reduce operation voltage of his optical phased arrays for laser beam steering. Dr. Dorschner's telephone number is (781) 860-3071.
4. We assisted Prof. Nabeel Riza of University of Central Florida to build liquid crystal light switches for telecommunication applications. Prof. Riza's phone number is (407) 823-6829.
5. We helped Dr. Gary Qian of DigiLens to lower the operation voltage of his holographic polymer-dispersed liquid crystals. Dr. Gary Qian's phone number is (408) 737-1100 x259.

7. New Discoveries or Inventions

During this report period, HRL has filed three patents related to AFOSR-funded research:

1. S. T. Wu, S. Marder and Q. T. Zhang
Colorless high dielectric compounds
(Filed April 1999)
2. S. T. Wu and M. Neubert
Polar diphenyl-diacetylene liquid crystals
(Filed, April 2000)
3. S. T. Wu, Z. Chai and L. R. Dalton
Polar bisolane liquid crystals
(Filed, July 2000).

8. Honors and Awards

S. T. Wu is a Fellow of the Optical Society of America (1993) and the Society for Information Display (2001). He received the 2000 special recognition award from the Society for Information Display.